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SUMMARY

Two cone-column solar-energy concentrators were evaluated in this investigation. Both models had a rim angle of 0.79 radian and an effective radius of 76 cm. The first model was a simplified version of the cone-column with a rigidized cone. This model had a calorimetric efficiency of about 0.55 at an aperture radius of 8.16 solar-image radii. If this efficiency could be attained with a model utilizing a low-mass membrane cone, the cone-column would be competitive with a petalous concentrator designed for use with a Rankine cycle system. The second model was constructed to study some of the problems associated with the fabrication of an accurate membrane cone. However, the efficiency of this model was only about 0.28 at an aperture radius of 8.16 solar-image radii. The low efficiency of this model is due to markoff and interference of cone gores.

The variation in efficiency for misalinement of the concentrator axis with the solar rays indicated that the performance of the cone-column was similar to that of a paraboloid. In addition, it was shown that small variations in misalinement can be compensated for by transverse displacements of the heat receiver.

INTRODUCTION

One of the major problems associated with the design of an orbital laboratory is the development of a system that will supply large amounts of electrical power. Dynamic conversion systems utilizing concentrated solar energy are considered candidates for supplying this power (ref. 1). Because large areas of solar radiation must be intercepted, expandable concentrators have received considerable attention as one means of achieving a compact launch package. (See, for example, refs. 2 and 3.)

One type of expandable concentrator which has been investigated is the cone-column (refs. 4 and 5). This type of concentrator utilizes both mechanical and optical folding and consists of a membrane cone and a telescoping coaxial column. Solar rays parallel to the concentrator axis are reflected from the cone to the column, back to the cone, and thence to the focus.

The purpose of the present investigation was to determine the concentrating efficiency of two cone-column models. The first test model (ref. 4) was a simplified version of the cone-column with a rigidized cone. This model allowed evaluation of the optical concept without becoming involved in the complexities of fabricating an accurate conical surface from a membrane material. The second model (ref. 5) was constructed to study the problems associated with the fabrication of an accurate membrane cone. Both models had a rim angle of 0.79 radian and an effective radius of 76 cm. Calorimetric efficiency was determined by surveying the focal region with a water-cooled calorimeter to measure the percentage of incident solar radiation absorbed by the calorimeter water. The calorimeter apertures used in this program had radii ranging from 1.11 to 8.16 solar-image radii. Such a range includes the optimum aperture size for using these concentrators with a dynamic-conversion power system.

SYMBOLS

Physical quantities in this paper are given in the International System of Units (SI). Factors relating this system to U.S. Customary Units are presented in reference 6.

f — concentrator design focal length, focal length of a paraboloid having the same effective radius (76 cm) and rim angle (0.79 radian) as the test models (see fig. 1(b)), 92 centimeters

f_a — distance from the calorimeter aperture to the vertex of the paraboloid described in definition of f, centimeters

R_a — radius of calorimeter aperture, centimeters

R_e — effective radius of cone or largest radius from which rays are reflected to the focus, 76 centimeters

R_i — calculated radius of solar image formed at focus by cone of rays reflected from vertex of the paraboloid described in definition of f, $f \tan \alpha$, 0.428 centimeter

x — displacement of center of calorimeter aperture from concentrator axis, centimeters

α — half-angle subtended by sun, 4.65 milliradians

β misalinement angle, angle between concentrator axis and solar rays, milliradians

η calorimetric efficiency of concentrator, ratio of energy absorbed by calorimeter water to energy incident on concentrator

η_g geometric efficiency, ratio of energy entering calorimeter to that specularly reflected from concentrator, η/ρ where ρ is the specular reflectance

MODELS

Basic Concepts

The concept of the cone-column solar concentrator as developed in reference 4 is the replacement of a paraboloidal mirror by an equivalent optically folded system consisting of cone and column reflectors. Since the paraboloid and the cone-column reflectors are optically equivalent, the focal point, rim angle, and image size of the paraboloid are preserved. The basic geometry of a cone-column concentrator is shown in figure 1(a) and the path of an incident ray is shown for both the cone-column and the equivalent paraboloid. Solar rays parallel to the cone axis are reflected toward the column, which acts as a paraboloid and concentrates the rays via the cone to the focus. The projected area of the column may become large (ref. 4), and incident rays that strike the column directly are lost. One method of reducing the projected area is to use a stepped column (fig. 1(b)) whose image is a conical Fresnel reflector (ref. 7). In addition to reducing the projected area, the stepped column may also reduce the column mass.

The basic configuration of the concentrator is defined by three parameters: the vertex half-angle of the cone, the rim angle, and the effective radius of the concentrator. A detailed analysis of the procedure used in selecting values for these parameters is given in reference 4.

Test Models

Two models constructed to assist in defining the problems associated with the fabrication of this type of concentrator were investigated. The basic dimensions common to both models are shown in figure 2. These models were designed to have a rim angle of 0.79 radian and an effective radius of 76 cm. The actual radius of the cone is slightly larger than 76 cm; however, energy reflected from outside this radius is lost. This geometrical configuration was chosen from both optical and structural considerations (ref. 4). Both models were constructed with heavy one-piece columns rather than the light telescoping versions that would be used for flight hardware. The columns were machined from steel and received a reflective coating of vacuum-deposited aluminum.

Reinforced-cone model.- Dimensions and fabrication details for the reinforced-cone model are given in figures 2 and 3. The nonfolding cone was fabricated by heat shrinking a one-piece cone of 25-μm-thick aluminized polyethylene terephthalate on a conical mold. The cone was stiffened, while still on the mold, by the application of an epoxy resin and reinforced by several layers of glass cloth impregnated with a polyester resin. Cables from the top of the column to the rim of the cone kept the cone and column concentric. A more detailed description of the reinforced-cone model is given in reference 4.

Membrane-cone model.- Dimensions and fabrication details for the membrane-cone model are given in figures 2 and 4. The foldable cone was made of 24 free-standing gores of 25-μm-thick aluminized polyethylene terephthalate. The gore ends were attached to a 16-cm-diameter plate near the cone vertex and to a metal torus at the base. Semicircular plastic stiffeners having the same width as the gore were bonded to the rear surface of each gore to eliminate wrinkling of the uniaxially stretched membrane. (See fig. 4.) The stiffeners were made from the same material as the cone but did not have the aluminum reflective coating. The bonding of the stiffeners to the gores resulted in a distortion (markoff) of the reflective surface seen in figure 5 as circumferential bands. Guy wires running from the torus at the cone base to a central hub attached to the column kept the cone in tension and concentric with the column. A more detailed description of the membrane-cone model is given in reference 5.

APPARATUS AND TESTS

The calorimetric evaluation was performed with the concentrator mounted on the solar tracker shown in figure 6. The tracker maintained any preset alinement angle between the concentrator axis and the solar rays to within ± 0.1 mrad. A water-cooled cavity-type calorimeter located in the focal region was equipped with aperture plates of various sizes.

Tests were performed to determine the effects of aperture size, transverse and axial location of the calorimeter, and misalinement of the optical axis with the solar rays. A distortion of the conical geometry of the membrane cone due to deflections of the gores under their own weight was observed during installation on the tracker. This distortion increased when the concentrator axis was tilted away from the vertical to track the sun. One method of reducing this distortion without changing the cone angle would be to increase gore tension by shortening the unstretched gores; however, the concentrator had no provision for individually adjusting the gore length. Therefore, preliminary calorimetric tests were made at various cone tensions by applying additional force to the torus to increase the cone height. The cone height setting that produced maximum efficiency was used for the remainder of the investigation.

The ranges of test variables were: calorimeter aperture sizes from $1.11R_i$ to $8.16R_i$, axial calorimeter movement of 0.06f, transverse calorimeter movement of $\pm 2.2R_i$, misalinement of the optical axis with the solar rays of ±40 mrad.

A complete description of the apparatus and test techniques can be found in reference 8.

ACCURACY OF DATA

The accuracy of the efficiency measurements presented herein has been estimated on the basis of repeatability of data and instrument accuracy at flow rates suitable for the calorimetric heat load with an aperture radius of $5.93R_i$. The heat load was dependent upon aperture size and concentrator efficiency, and the flow rate of the water was varied to obtain water temperature increases large enough for accurate measurement. The estimated accuracy of the efficiencies reported herein is ±0.015 for the reinforced-cone model and ±0.030 for the membrane-cone model. A part of the larger experimental error for the membrane-cone model was due to its lower efficiency, which required lower flow rates. Interference between gore stiffeners that prevented return of the gores to their original position after flutter in slight breezes also contributed to the experimental error.

RESULTS AND DISCUSSION

A calorimetric search of the focal region of each model was conducted to determine the calorimeter location that produced maximum efficiency. The variation in concentrator efficiency with calorimeter position and with alinement of the concentrator axis was also evaluated during this investigation. Parameters not being varied in a particular test were kept near the optimum test values.

Reinforced-Cone Model

The variation in concentrator efficiency with the location of the calorimeter along the optical axis is shown for the reinforced-cone model in figure 7(a). The dimensions defining the axial location of the calorimeter (f_a/f) are measured from the vertex of the paraboloidal image of column segment 1 (fig. 1(b)). The focal setting for maximum efficiency was near the design value ($f_a/f = 1.0$) and showed no systematic variation with aperture size. Concentrator efficiency is relatively insensitive to small changes in axial location of the calorimeter. This insensitivity is due to surface slope errors in the concentrator which cause a large energy distribution in the focal plane.

The variation in concentrator efficiency with transverse location of the calorimeter aperture is shown in figure 7(b). The transverse location of the calorimeter has been normalized by R_i, the radius of the solar image. The location for maximum efficiency with the smallest aperture size was selected as the zero reference position. With all aperture sizes, maximum efficiency was reached near this zero location. The efficiency curve for the largest aperture ratio (8.16) was relatively flat, indicating that most of the high-intensity portion of the energy distribution was enclosed by the aperture. Measurements made on the other lateral axis gave results similar to the ones shown in the figure.

The maximum calorimetric efficiency obtained with each aperture during the focal-region searches is presented as a function of aperture ratio in figure 7(c). At the larger aperture ratios the curve appears to reach a maximum value, which indicates that nearly all of the specularly reflected energy is entering the aperture. Since calorimeter losses were small, the maximum calorimetric efficiency is considered equal to the specular reflectance of the concentrator. The specular reflectance of this model is about 0.55, which is low in comparison with the specular reflectance of 0.905 measured on a stretch-formed aluminum paraboloid (ref. 9). Solar energy incident on the cone-column is attenuated by three reflection losses, whereas only one reflection loss occurs with the paraboloid. If a specular reflectance of 0.90 is assumed for the metallic column of the reinforced-cone model, an average specular reflectance of about 0.78 can be calculated for each of the two reflections from the cone. This is somewhat lower than the specular reflectance of 0.83 measured on fresh samples of aluminized polyethylene terephthalate (ref. 2). However, the calculated reflectance of the cone (0.78) is reasonable since some degradation might be expected from heat shrinking the membrane on the mold and from the rigidizing process. Consequently the measured reflectance of 0.55 is reasonable for the reinforced-cone model tested in this investigation.

Additional tests were run to determine the effect of misalinement of the concentrator axis with the solar rays and to determine the extent to which this misalinement can be compensated for by lateral movement of the calorimeter. The variation in efficiency for angular misalinement of the concentrator axis with the solar rays is shown in figure 7(d). Maximum efficiency was attained at the same setting for all aperture sizes; however, the variation for the largest aperture was not symmetrical about $\beta = 0$, a result which may be due to an unsymmetrical distribution of energy in the focal plane. Although accurate orientation is required with small apertures, the orientation requirements are less stringent for the $8.16R_i$ aperture size, which is near the $7.6R_i$ aperture size considered for use with a dynamic conversion system (ref. 10).

The combined effects of angular misalinement and transverse location of the calorimeter are shown in figure 7(e) for two apertures. Data for the $8.16R_i$ aperture indicate that small errors in calorimeter location or concentrator alinement can be compensated for by adjustments to the other component. For example, an alinement error of -17 mrad can be compensated for by a $-3.24R_i$ transverse displacement of the calorimeter aperture. The data for the $4.44R_i$ aperture are presented to indicate typical trends for apertures not enclosing all of the concentrator energy distribution. This aperture has trends similar to the $8.16R_i$ aperture; however, complete compensation is not achieved at either transverse displacement because of the slightly larger image size produced by misalinement.

An analysis of the cone-column reported in reference 4 indicates that the variation in efficiency with misorientation should be the same as for a paraboloid. Figure 8 compares the variation in efficiency with misorientation for the cone-column and a paraboloidal concentrator reported in reference 9. The model of reference 9 was a 76-cm-radius one-piece paraboloid fabricated from stretch-formed aluminum. The two models had considerably different calorimetric efficiencies, although they had comparable geometric efficiencies. Since misalinement effects are independent of specular reflectance, the geometric efficiency is used in this comparison. The change in efficiency with misorientation is about the same for the cone-column and the paraboloid; thus the analysis reported in reference 4 is verified for the range of angles investigated.

Membrane-Cone Model

As noted previously, the cone gores sagged under the asymmetrical gravity loading encountered when the concentrator axis was moved away from the vertical to track the sun. Since the only means of adjusting the gore tension was by changing the cone height, preliminary tests were run to determine whether concentrator efficiency could be increased by extending the cone to heights greater than the design value. The results of preliminary calorimetric tests at cone heights ranging from the design height to 7.9 mm greater than the design height are presented in figure 9(a). Maximum efficiency was obtained with the cone stretched to a height 6.4 mm greater than the design value, and all subsequent data were obtained at this setting. At all cone heights the concentrator focal length was shorter than the design value. The shorter focal length at the design height was probably due to sagging of the cone gores. The shorter focal length with the extended cone resulted from the change in cone angle. The calculated decrease in focal length was different for each column segment, and the weighted average of all segments for the 6.4-mm cone extension indicated that the focal length should be about 0.97f. This calculated focal length shows good agreement with the experimental data presented in figure 9(a).

Figure 9(b) presents calorimetric efficiency as a function of axial location of the calorimeter. The concentrator focus is not well defined but the optimum calorimeter position appears to be about 0.97f for all aperture sizes. The failure of the concentrator to exhibit a well-defined focal point may be due to several conditions, one of which is defocusing caused by increasing the cone height. Another condition which could cause defocusing is the markoff condition seen in figure 5, which is due to bonding the stiffeners to the gores.

The variation in efficiency with aperture size for the membrane-cone model is compared with the data for the reinforced-cone model in figure 9(c). Also shown in figure 9(c) is the calorimetric efficiency reported in reference 10 for a single panel of a 9.8-m-diameter expandable paraboloid at the design aperture ratio selected for a Rankine cycle converter. The membrane-cone model was considerably less efficient than the reinforced-cone model for all aperture sizes and reached an efficiency of only 0.28 with the largest aperture tested. Since the membrane-cone model shows a continuing increase in efficiency with increase in aperture ratio, its focal-plane energy distribution must be larger than the largest test aperture. This large energy distribution and the resulting low efficiency of the membrane-cone model is due to membrane wrinkling and markoff at the attachment locations of the gore stiffeners (fig. 5).

A measure of the potential utility of various concentrator designs is the power-mass relation. The concentrator specific mass estimated for an 18.3-m-diameter cone-column (0.673 kg/m^2) in reference 5 is lower than that estimated for a 9.8-m-diameter expandable paraboloid (1.22 kg/m^2) in reference 10. On the basis of these estimated specific masses and the calorimetric efficiencies of the reinforced-cone model, it would take an 11.1-m-diameter cone-column to concentrate the same amount of solar energy as a 9.8-m-diameter petalous paraboloid into a 36.6-cm-diameter aperture (design aperture for use with the paraboloid). From the preceding information it appears that the cone-column would be about 14 percent larger in diameter than the paraboloid but have 22 percent less mass. Therefore, if a concentrator with a membrane cone and telescoping column could be fabricated to have the performance of the reinforced-cone model it would be competitive with petalous concentrators and suitable for use with Rankine cycle convertors. However, some method of eliminating the wrinkling and markoff in the membrane cone must be found before an efficient low-mass model can be fabricated.

CONCLUDING REMARKS

Two 76-cm-radius cone-column solar concentrators were tested in sunlight. An efficiency of about 0.55 was obtained at an aperture radius of 8.16 solar-image radii for the reinforced-cone model. If this efficiency could be attained with a low-mass membrane cone, the cone-column would be competitive with a petalous concentrator. However, the efficiency of the membrane-cone model was only 0.28 for the same aperture. The low efficiency of the membrane model is due to markoff and interference of cone gores. The variation in efficiency with misorientation of the cone-column concentrator was similar to that for a paraboloidal concentrator having comparable geometric efficiency.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 16, 1969,
120-33-06-03-23.

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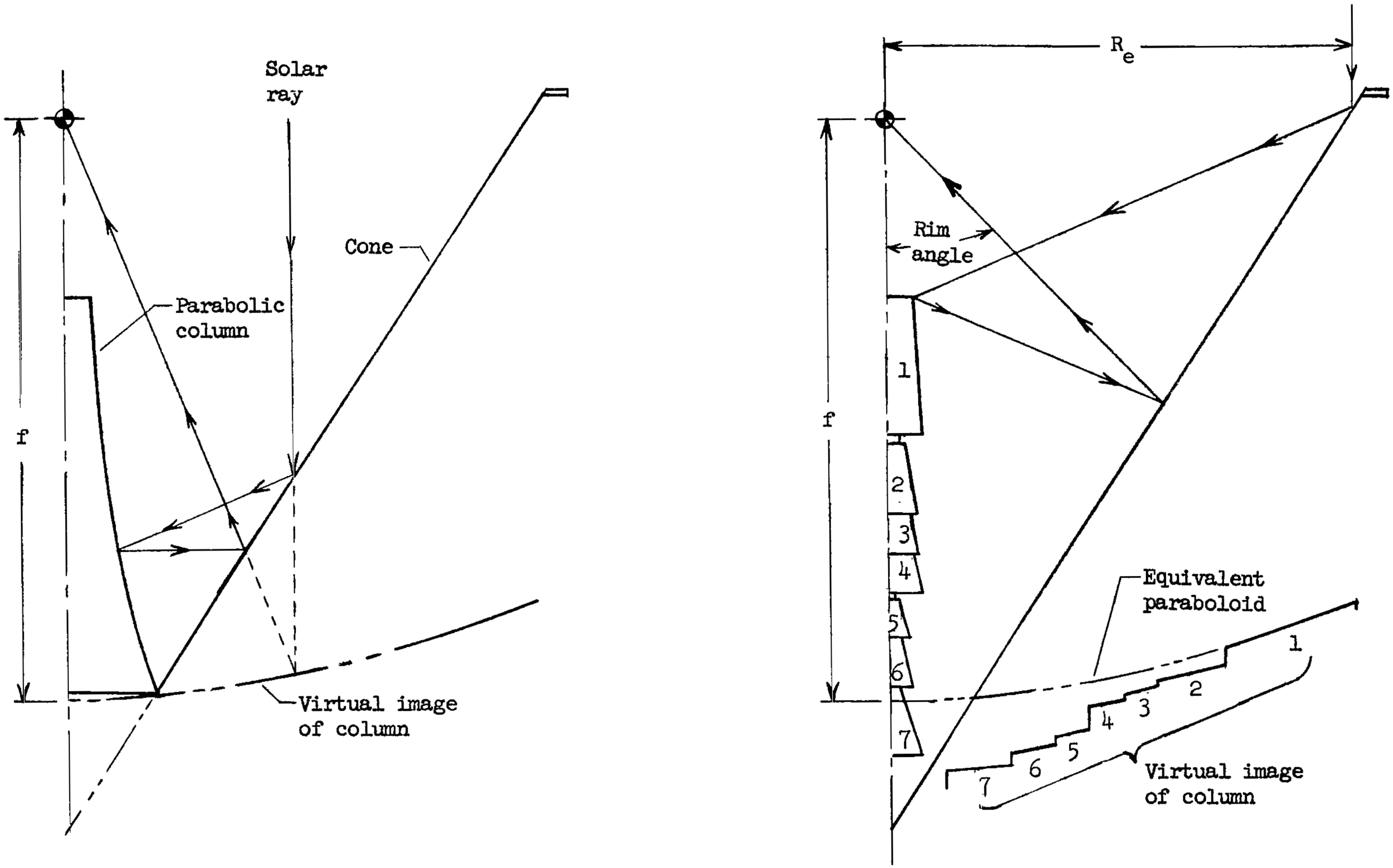
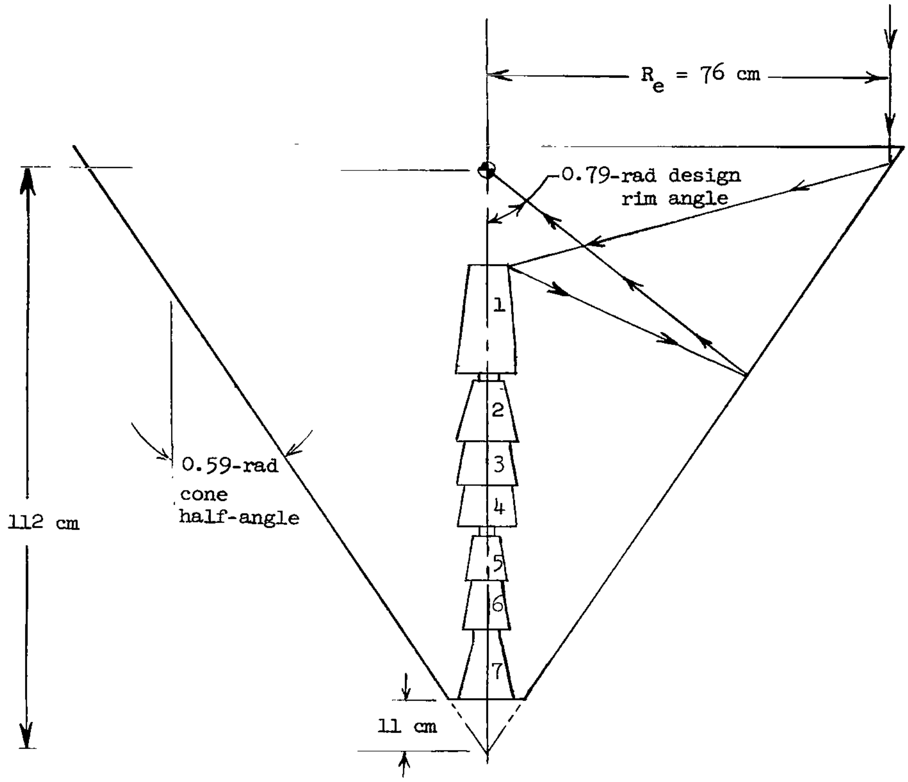


(a) Optical equivalent of paraboloid.

(b) Optical equivalent of conical Fresnel reflector.

Figure 1.- Diagrams illustrating the basic concept of a cone-column concentrator.



COLUMN DIMENSIONS				
Column segment	Segment radius, cm		Segment length, cm	Focal length (nominal), cm
	Top	Base		
1	4.13	5.26	23.0	92.0
2	2.82	4.45	11.6	94.5
3	3.73	4.79	5.7	95.2
4	4.07	5.32	5.8	96.0
5	1.76	3.15	5.5	99.6
6	1.76	3.79	7.0	101.0
7	1.73	5.08	9.9	103.4

Figure 2.- Dimensions common to both models.

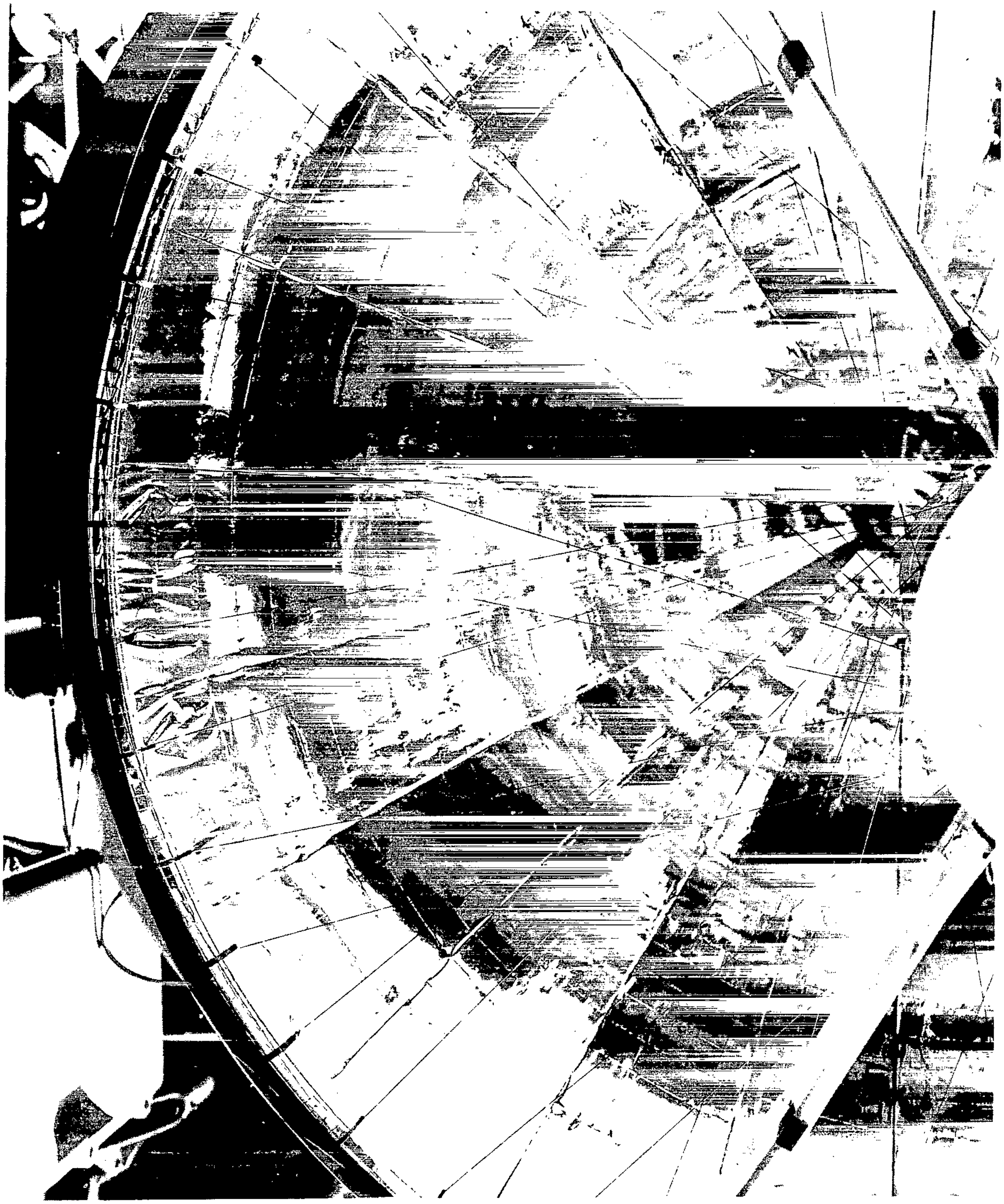


Figure 5.- Photograph of membrane-cone model showing markoff of stiffeners on cone. L-65-6849

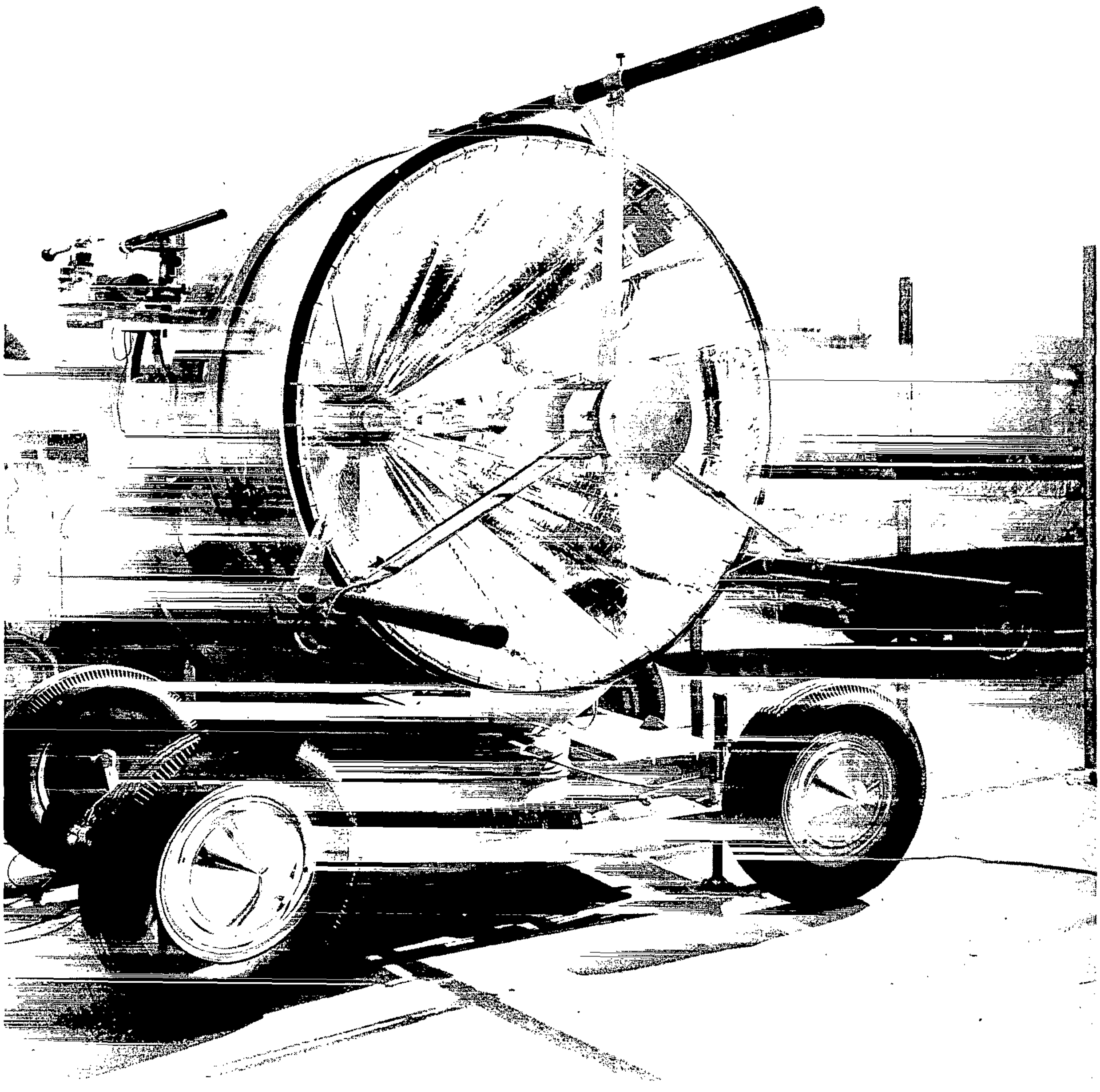
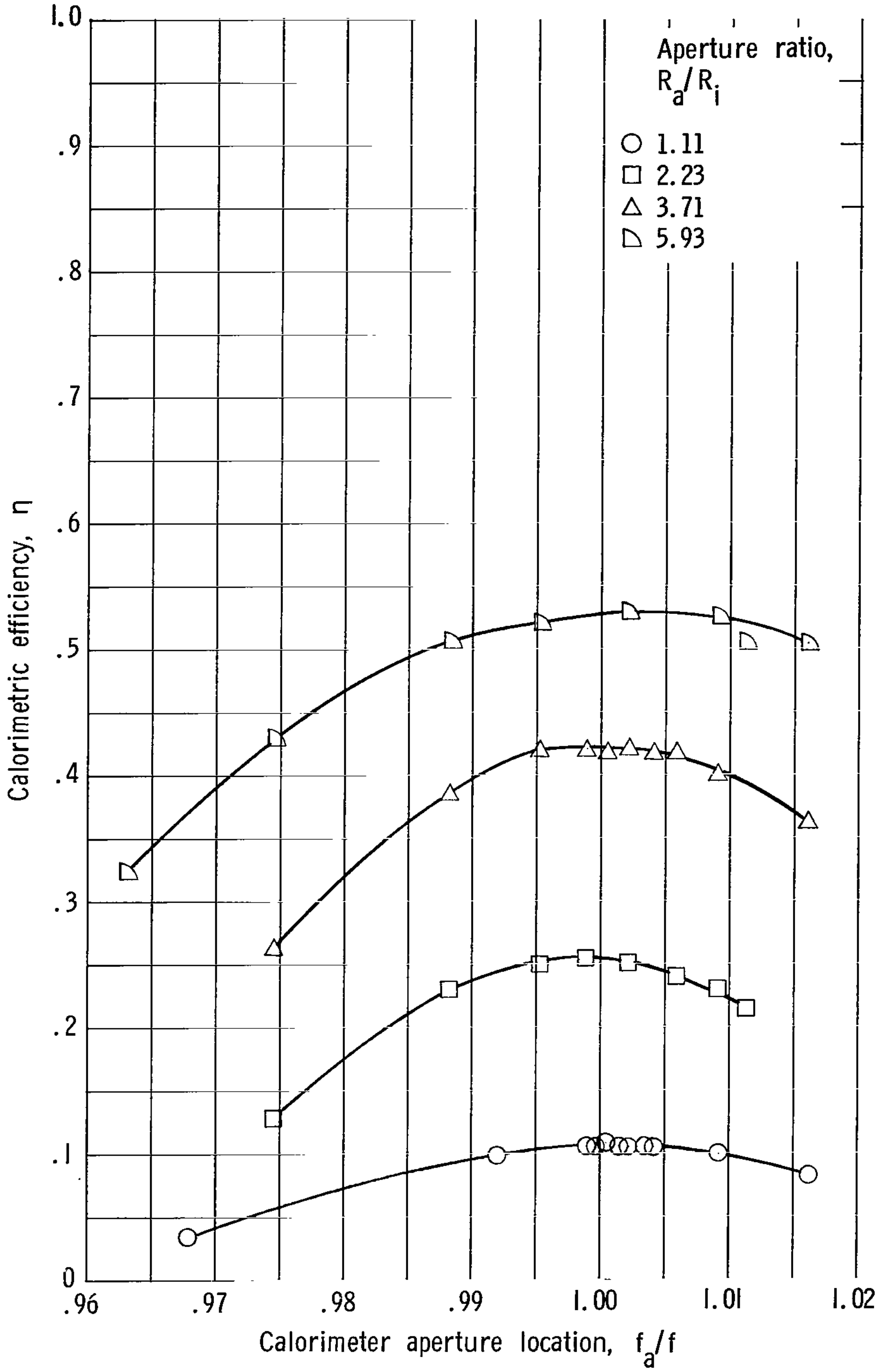
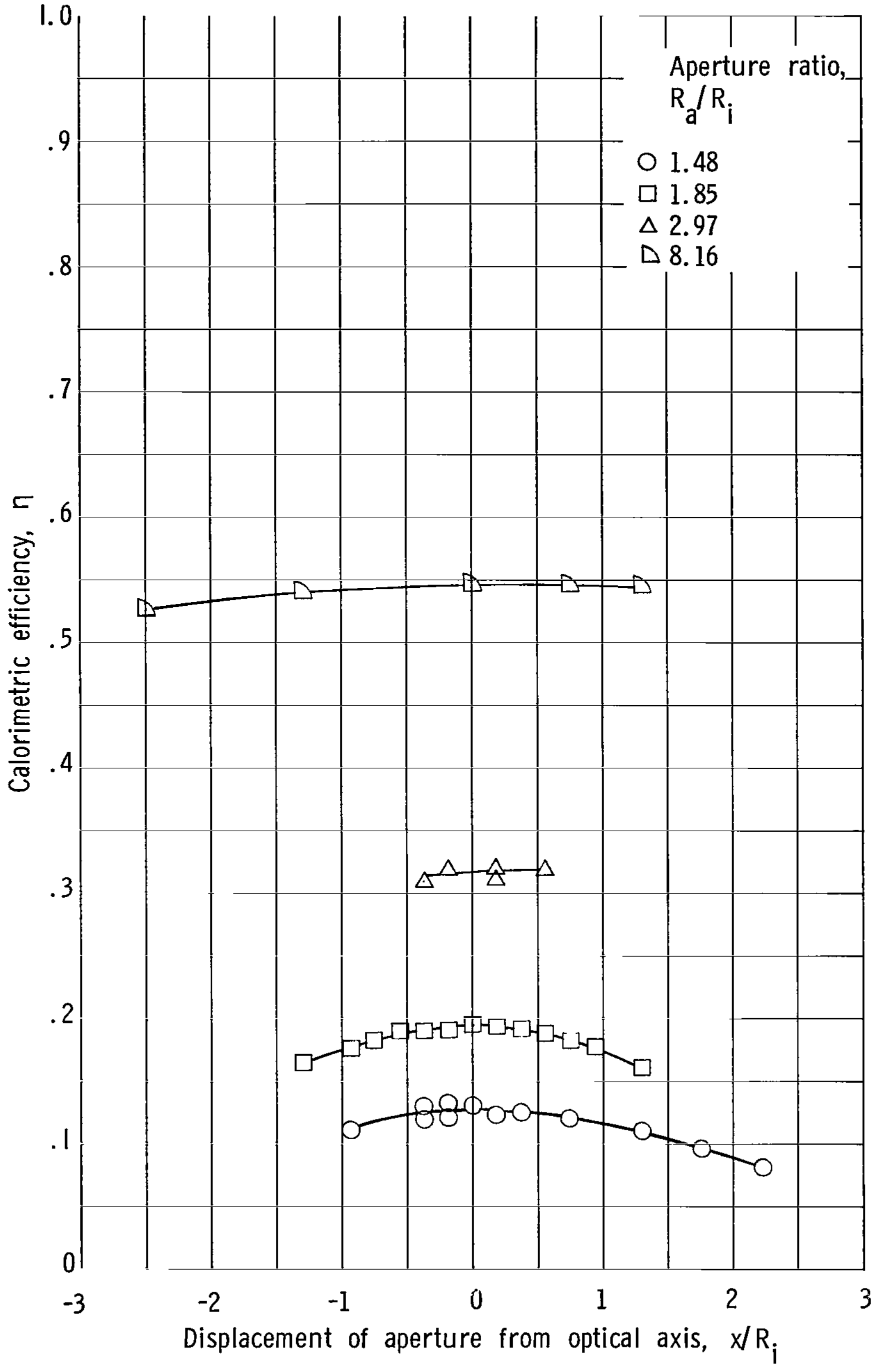


Figure 6.- Photograph of membrane-cone model mounted on the solar tracker. L-65-6848



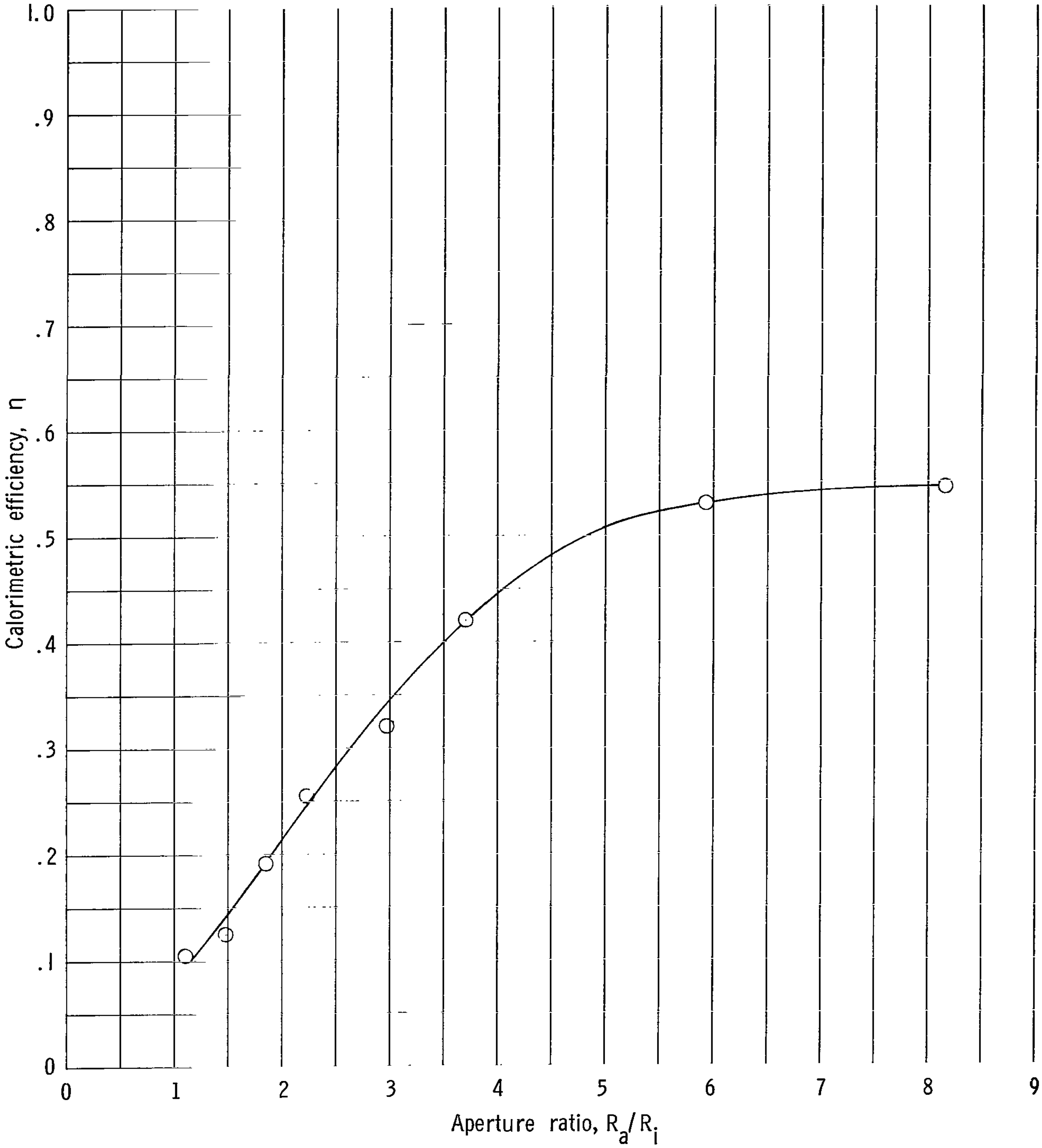
(a) Variation in concentrator efficiency with axial location of the calorimeter.

Figure 7.- Calorimetric efficiency for the reinforced-cone model.



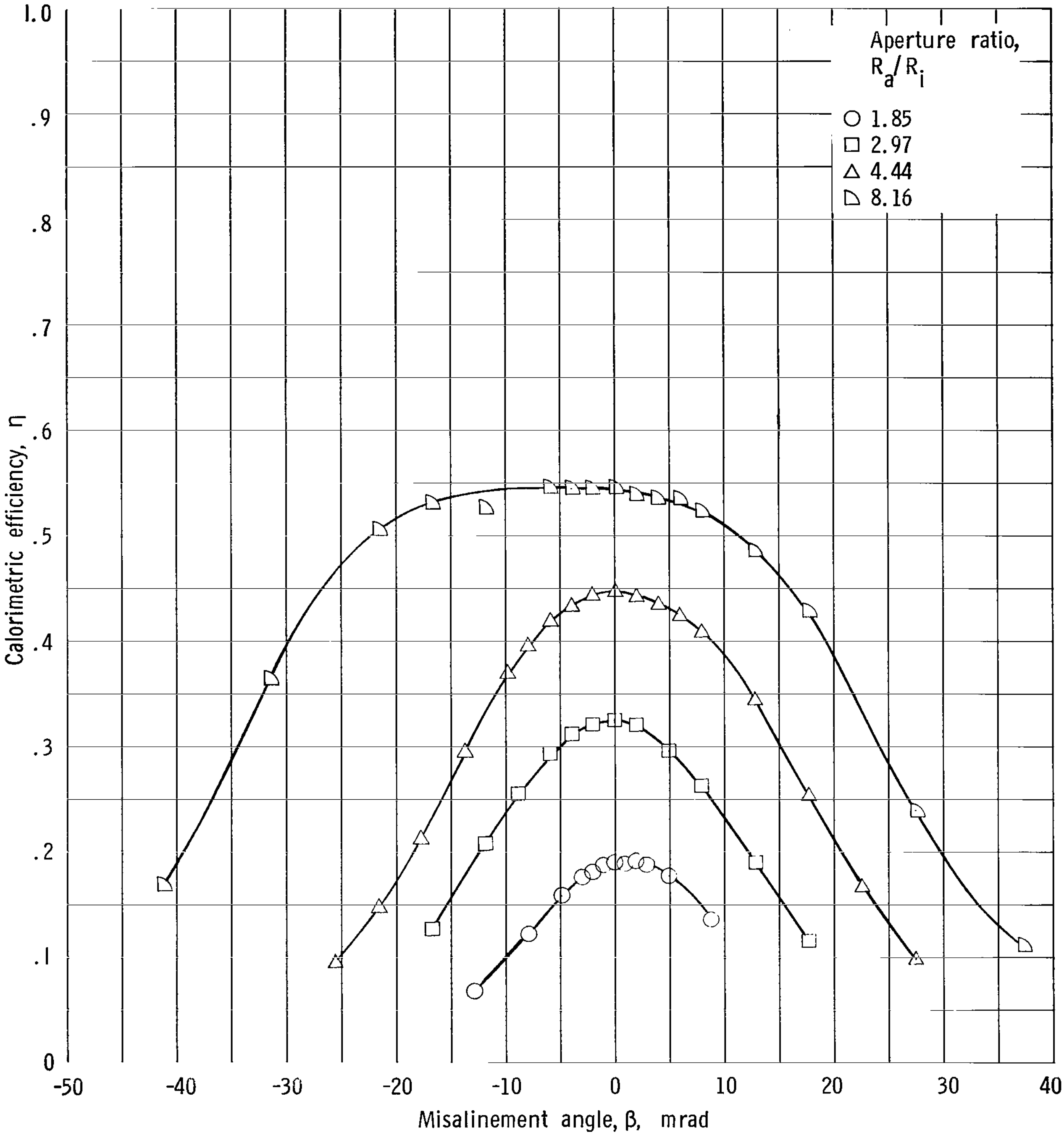
(b) Variation in concentrator efficiency with transverse location of the calorimeter.

Figure 7.- Continued.



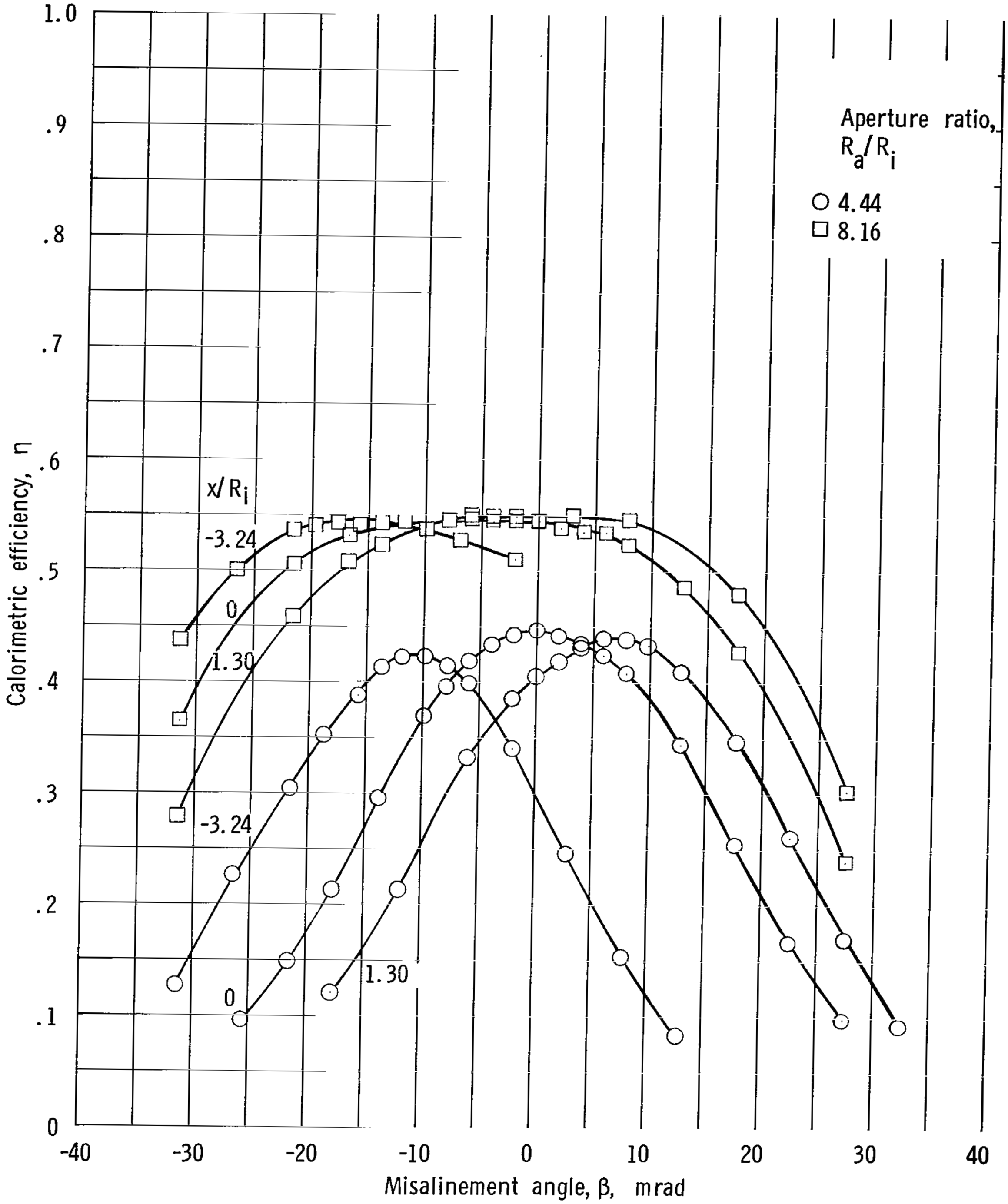
(c) Variation in concentrator efficiency with aperture ratio.

Figure 7.- Continued.



(d) Variation in concentrator efficiency with angular misalinement of the optical axis with the solar rays.

Figure 7.- Continued.



(e) Variation in concentrator efficiency with combined angular misalinement and transverse mislocation.

Figure 7.- Concluded.

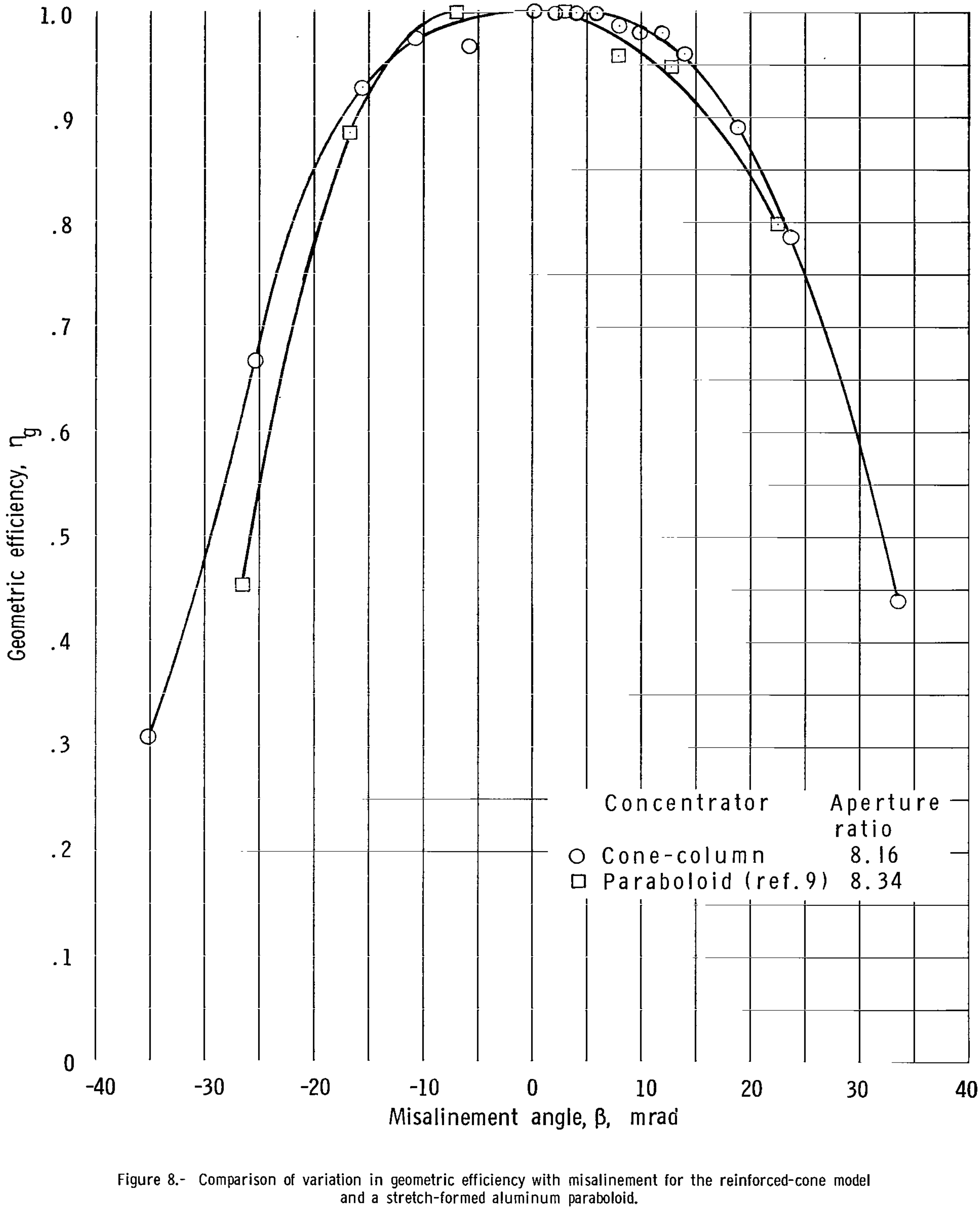
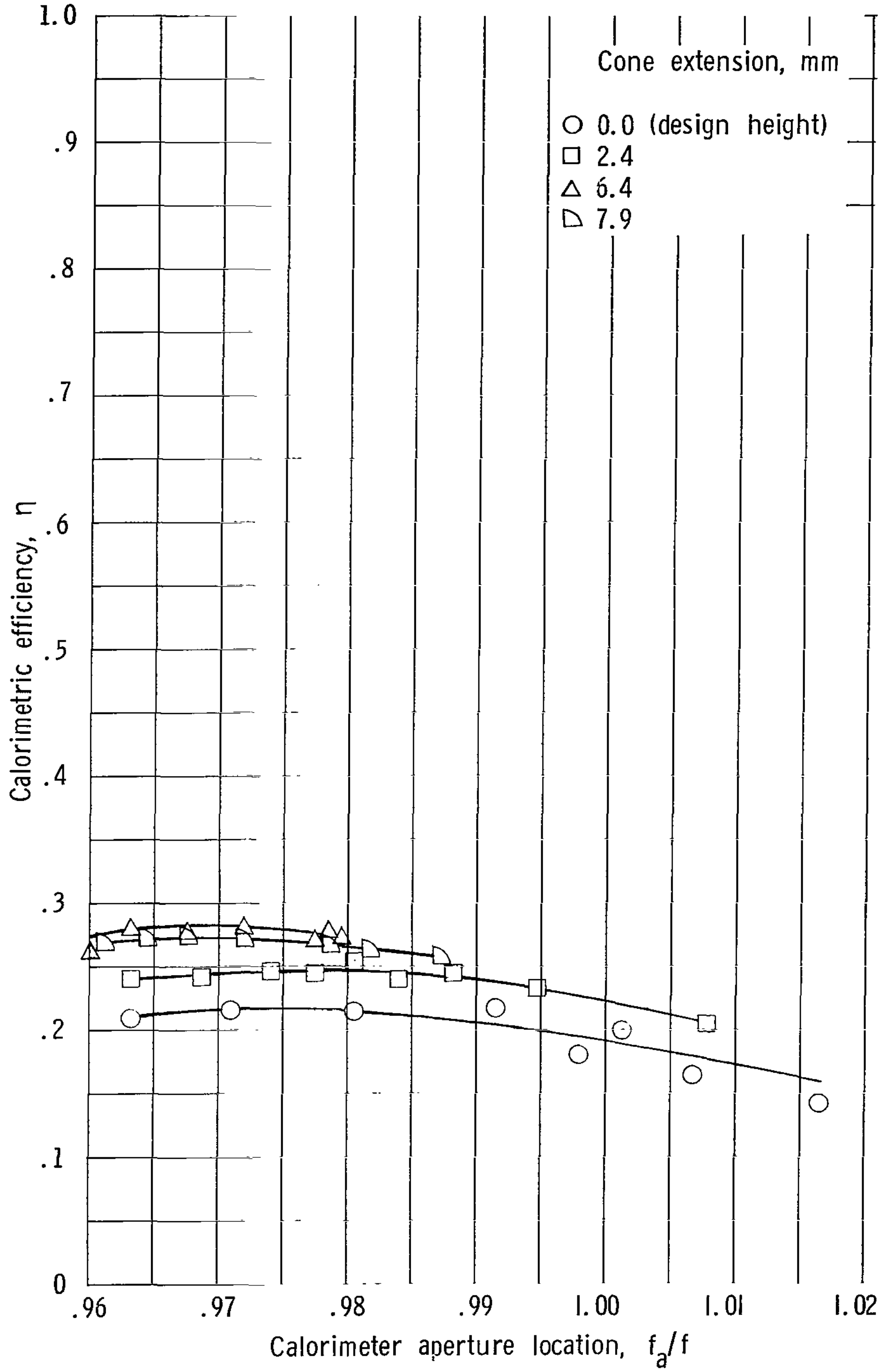
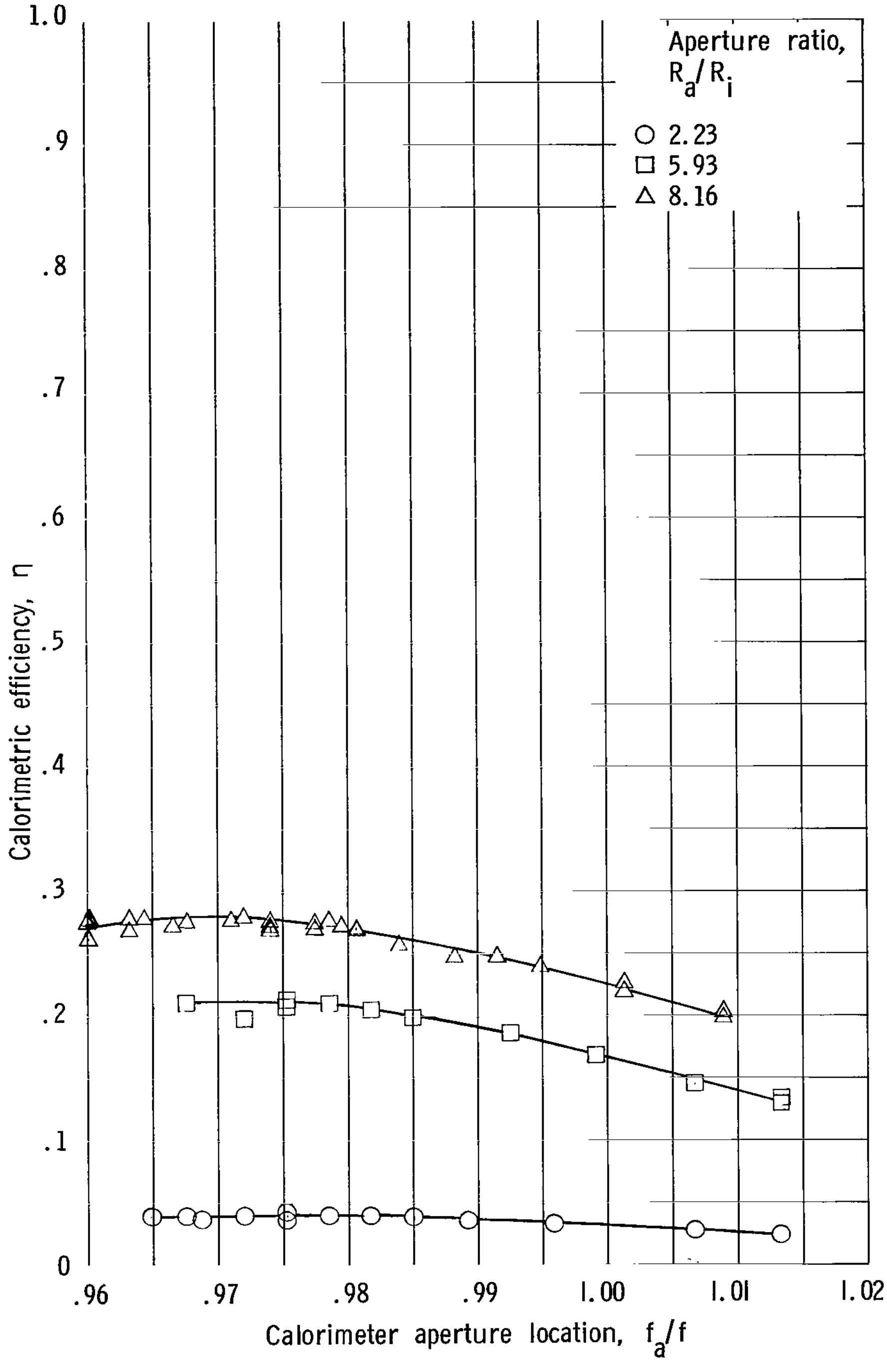


Figure 8.- Comparison of variation in geometric efficiency with misalinement for the reinforced-cone model and a stretch-formed aluminum paraboloid.



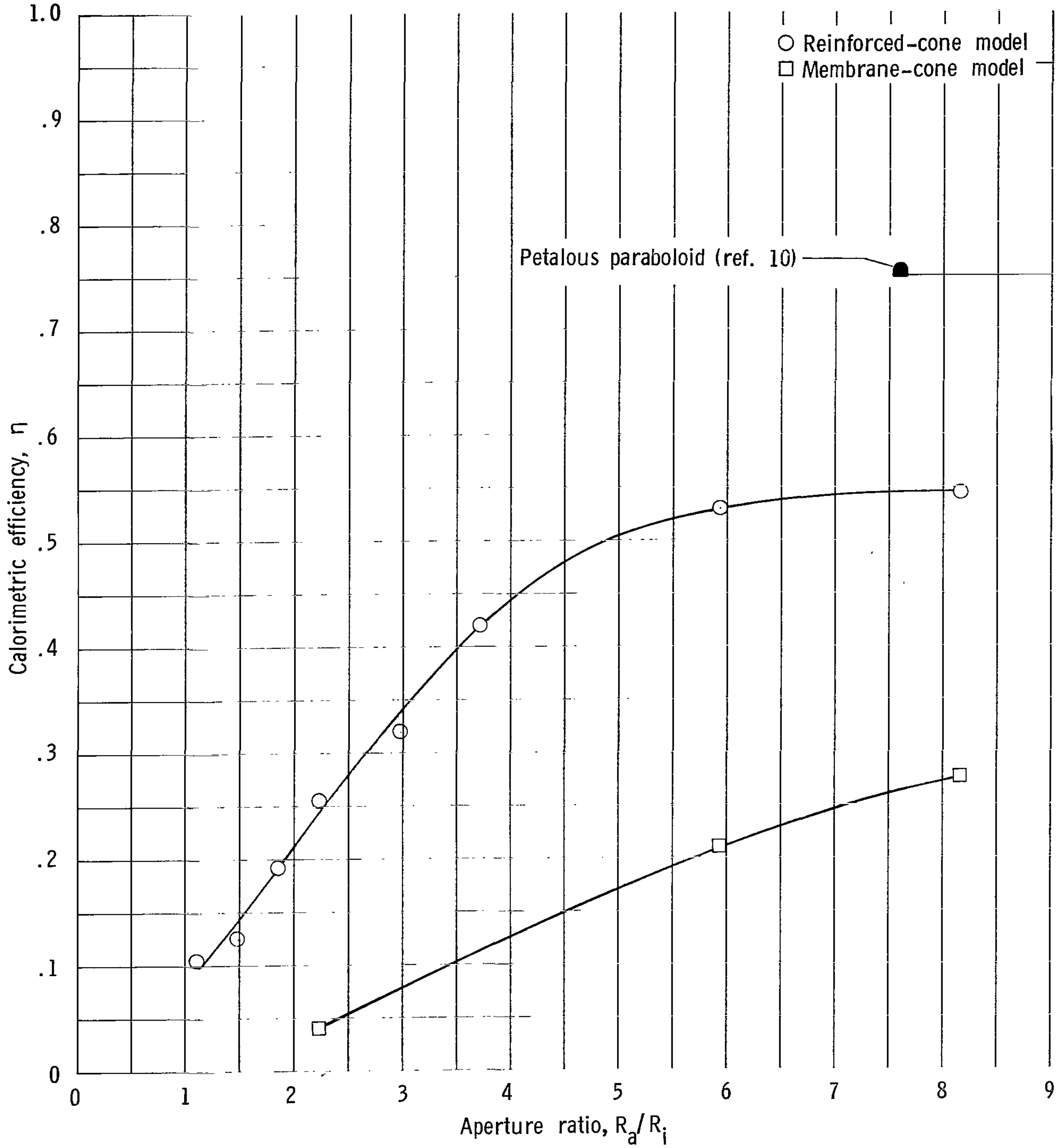
(a) Effect of extending cone. $R_a/R_i = 8.16$.

Figure 9.- Calorimetric efficiency of the membrane-cone model.



(b) Variation in concentrator efficiency with axial location of the calorimeter.

Figure 9.- Continued.



(c) Variation in concentrator efficiency with aperture ratio.

Figure 9.- Concluded.

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